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Frequency Regulation in AC Microgrid with and without Electric Vehicle Using Multiverse-Optimized Fractional Order- PID controller

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Abstract: This paper presents the design and implementation of a novel control scheme for frequency regulation in an AC microgrid, subjected to varying operating conditions, using fractional order proportional integral derivative (FOPID) controller with its parameters optimized employing multi-verse optimizer (MVO) evolutionary algorithm. For the comparative analysis, proportional integral derivative (PID) and fractional order proportional integral (FOPI) controllers, both optimally tuned using MVO, are also implemented. Further, the impact of electric vehicle (EV) on system performance is analyzed. Integral of time multiplied absolute error (ITAE) is considered as the cost function in the optimization process whereas, the settling time and peak undershoot serve as the performance indices and a step change in load is taken as the perturbation. The proposed control scheme is tested for robustness against system parametric changes in the range of ± 25 besides random step load varying both in magnitude and time scale. The proposed MVO optimized FOPID controller outperforms other control schemes implemented in this work and proves to be very effective in frequency regulation in the AC microgrid comprising the renewable energy sources (RESs), diesel engine generator (DEG), and the energy storage systems (ESS). System Modeling and simulations are performed in MATLAB/Simulink.

Keywords: MVO, AC Microgrid, Frequency Regulation, Renewable Energy Sources, Electric Vehicle

1. INTRODUCTION

With the ever increasing electricity demand and adverse impact of the conventional sources of energy on environment, integration of RESs such as wind, solar etc. into the existing power systems has progressively increased. RESs have many advantages, however, the increased penetration of RESs results in increased complexity and uncertainty in the power system. There are many technical challenges associated with RESs that need to be addressed for the stable operation of the power system having integration of RESs. This scenario requires the use of ESSs like batteries, SMES, flywheel etc. to compensate for the unpredictability of the RESs due to their weather dependency. Control strategies also play an important role in the efficient operation of these hybrid power systems where the RESs are integrated in the form of microgrid structures which are nothing but the clusters of RESs, energy storage system (ESSs), and local loads [1][2]. The microgrid concept [3][4] made it easier to integrate RESs, the ESSs and the controllable loads as one cluster. Such microgrid structure, connected to the main grid through a static switch called point of common coupling (PCC), acts as a single entity so far as the main grid is concerned and responds to the control signals of the main grid accordingly. Microgrid can be operated in two modes of operations: islanded mode and grid-connected mode [5]. When the microgrid is operating in grid-connected mode, the connected loads are fed through main grid whereas, if the microgrid is operating in islanded mode, the connected loads are taken care of by the RESs, ESSs and the DEG so as to maintain the active power balance between generation and loads thus regulating the frequency. Many control approaches have been proposed for frequency regulation in AC microgrid under different operating modes and conditions. The significance of frequency regulation and various control methodologies used therefore in islanded mode are reported in literature [6]. Droop control coupled with battery energy storage system (BESS) is reported in [7] for improved transient frequency response in an islanded microgrid. An active power control is proposed in [8] wherein by keeping the ESS-state-of charge (SOC) in safe limits by way of load consumption and generated

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PV system power, the microgrid system frequency is stabilized. In case of the grid connected mode, the regulation of frequency is governed by the main grid frequency in which demand response plays an important role. Authors in [9] proposed a demand response based scheme that provides reasonably cheaper and reliable alternative solution to conventional spinning reserve. An algorithm is put forth in [10] keeping into consideration the behavioral aspect of the domestic consumer using an automatic meter reading in conjunction with detection algorithm. A narrative demand response model is reported in [11] based only on the daily consumption pattern without bothering about the price elasticity of demand forecast. These days, with the availability of smart technologies, monitoring of energy usage at the consumer level has become easier [12] that has positively impacted the frequency regulation as well.

Combined use of particle swarm optimization (PSO) and fuzzy logic is proposed in [2] for optimal tuning of the PI controller, as used for frequency regulation in AC microgrid which results in an improved performance under random variations of load and even when the system is affected by the nonlinearities and disturbances. Authors in [13] presented a generalized droop control scheme, synergized with adaptive neural fuzzy, for islanded microgrid that ensures efficient regulation of the dynamic behavior under load perturbations. Intelligent control techniques based on fuzzy gain scheduling based PID controller [14], adaptive neural fuzzy inference system (ANFIS) based PID controller [15], and genetic algorithm (GA) tuned PID controller [16] have been proposed for islanded AC microgrid to regulate the system frequency with varying weather conditions.

Biogeography-based optimization algorithm based Linear Quadratic Regulator (LQR) controller is reported in [17] that mitigates the frequency deviations the microgrid. A PSO based optimal control strategy is put forth in [18] to take care of the transition of the microgrid to islanding state. Authors in [19] proposed a new time-varying controller based on General Type II Fuzzy Logic, incorporating the vehicle to grid technique, for frequency regulation in an islanding microgrid subjected to load variations and varying operating conditions. A virtual droop control method, as proposed in [20], results in improved performance vis-à-vis the droop control methods, in different operating modes of microgrid in respect of maintaining both the frequency and voltage constant. Authors in [21] made use of the linear quadratic differential game theory for frequency regulation in an islanded microgrid having multiple DGs.

Likewise, various optimization techniques/algorithms have been utilized by many authors for optimal tuning of controller parameters for frequency regulation in microgrids and conventional power systems. In [22], [23], authors have reported the use of differential evolution (DE) algorithm for optimal tuning of the controller as used for load frequency control. Ant lion optimization (ALO) has been made use of by authors in [24] for automatic generation control in a multi-area power system and its superiority is established over DE and PSO. Drawing inspiration from the Big Bang theory, Mirjalili et al. [25] proposed an efficient optimization algorithm, known as the MVO, and proved its effectiveness using various benchmark problems of optimization. The authors in [26],[27] demonstrated the potential use of MVO for optimization of controller parameters in load frequency control problems and proved its efficacy over ALO, teacher learning based optimization (TLBO), PSO, and DE algorithms.

EV is an evolving trend nowadays world over in the vehicle industry owing to the growing concern for environment and need for energy saving [28],[29]. EV technology helps reduce smog precursors, greenhouse gases, and gasoline consumption. When the EV is connected with the electric grid, the flow of power can be bidirectional: it acts as a load when in charging state [30] and as a power source when in discharging state [31]. Car usage statistical data shows that during almost 95% of the day, the cars remain in an idle mode meaning thereby that most of the EVs connected to the main grid are in charging state. With the fast development in the EV technology, the energy stored in batteries becomes extensively available and by way of using the vehicle to grid (V2G) technique, the EVs can serve as the distributed energy storage systems. Due to flexibility of operation and load supporting ability, EVs are coming handy as the alternate ESSs for the stable operation of an islanded microgrid [32].

The conventional controllers do not ensure guaranteed frequency regulation with V2G and other units integrated [33],[34] because these are not tuned for all operating conditions and variability of parameters. In literature, many different control concepts have been designed and proposed such as conventional PID control [2], adaptive control [34], intelligent control [35], and robust control [34] for establishing good frequency regulation. Proper coordination of EV with a blade pitch angle of wind turbine generator (WTG) for the microgrid frequency regulation with model predictive control (MPC) is presented in [36] that makes the wind power production smooth so as to decrease the number of EVs required. Robust H-infinity method for frequency regulation in hybrid DG system is studied in [37] although it involves high complexity. Small-signal stability analysis for an islanded microgrid having ESS integrated is presented in [38]. Islanded microgrid with hierarchical control structure is presented in [39].

In the light of the aforementioned background, this paper presents the design and implementation of the FOPID controller optimally tuned using MVO for the frequency regulation in an islanded AC microgrid. The rest of the paper is organized as follows: Section II details the general structure of the AC microgrid, while in Section III is described the modeling of EV and Section IV describes the control structure of the proposed MVO optimized FOPID controller. Section V is utilized to present the results and finally, Section VI concludes the findings.

2. SYSTEM UNDER STUDY

Controlling of microgrid system in islanded mode becomes important than grid-connected mode, so microgrid islanded mode is considered as a case study. The islanded AC microgrid system, considered for study and shown in Figure 1, comprises WTG, photovoltaic (PV) system, DEG, fuel cell (FC), flywheel energy storage system (FESS), battery energy storage system (BESS), and the EV. With each of the DG source connected in the microgrid, there are associated power electronics interface to ensure proper conversion and synchronization of AC and DC sources besides the respective switch for dealing with the emergencies or maintenance. The ratings of the DG sources and the loads are as specified in Table 1[40] whereas; Table 2 [40] gives the parametric values. P_{L1} is acting as the fixed load and P_{L2} as the variable auxiliary load. The power produced by DEG acts as a spinning reserve and plays a significant role in frequency regulation. The frequency response model is depicted in Figure 2. For detailed explanation of the DGs, the readers are referred to [38]. The output powers of the DGs connected to the microgrid being variable and intermittent requires efficient and effective control strategies to deal with undesirable dynamic impacts on the system stability and performance.

The total generated power (P_s) can be expressed as under:

$$P_S = P_{PV} + P_{WTG} + P_{FC} + P_{EV} + P_{DEG} \mp P_{BESS} \mp P_{FESS} \quad (1)$$

Where, P_{FC}, P_{PV}, P_{WTG}, P_{DEG}, P_{EV}, P_{BESS}, and P_{FESS} are the output powers of FC, PV, WTG, DEG, EV, BESS, and FESS, respectively.

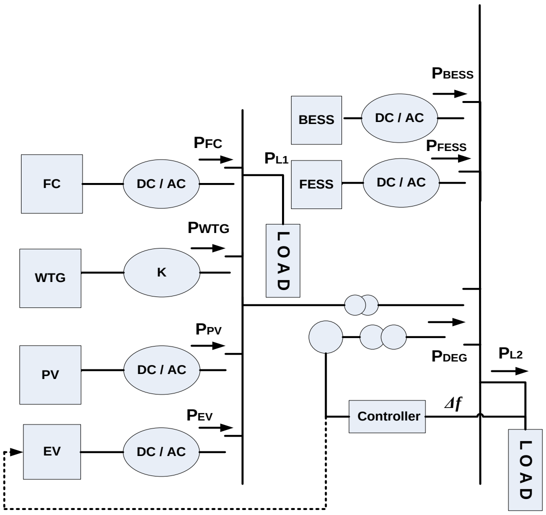

Figure 1. AC Microgrid System

Where, P_{FC}, P_{PV}, P_{WTG}, P_{DEG} and P_{EV} are the output powers of respective sources, indicated by the usual meanings of the subscripts, connected in the microgrid.

TABLE 1 LOAD AND DG UNITS RATING

DG Source	Rated Power (KW)	Load in (KW)	
PV	25	P_{L1}	220
WTG	125		
FC	70		
DEG	150	P_{L2}	200
BESS	40		
FESS	40		

TABLE 2 MICROGRID PARAMETER VALUES

Parameter	Values
Tg (s)	0.08
$T_{I/c}$ (s)	0.004
T_t (s)	0.4
T_{IN} (s)	0.04
T_{BESS} (s)	0.1
T_{FESS} (s)	0.1
D (pu/Hz)	0.015
R (Hz/pu)	3
H (pu s)	0.1667

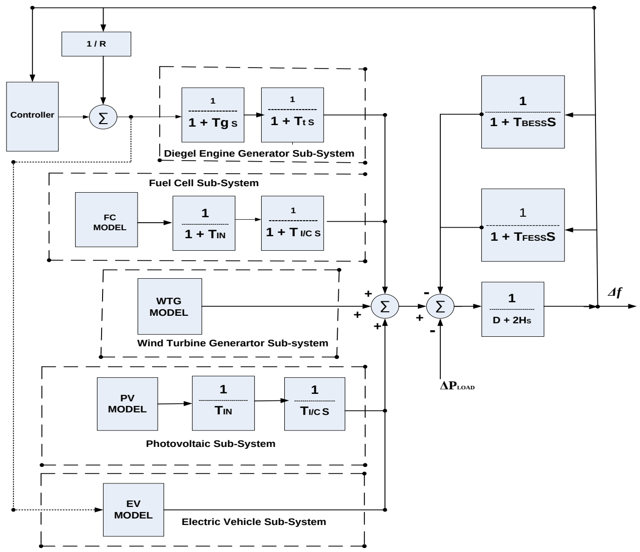

Figure 2. Frequency Response Model of AC Microgrid System

3. MODELLING OF PLUG-IN-ELECTRIC VEHICLE

A plug-in electric vehicle (EV) model, as adapted from [41],[42], is shown in Figure 3 wherein the frequency deviation signal (Δ_f) acts as input to the plug-in EV and charging/discharging power of the plug-in EV is available on its output. Battery capacity is represented by ±B_{kw}, plug-in EV time constant is represented by T whereas s represents the complex frequency variable. Battery energy is represented by E with $E_{\max}$ and $E_{\min}$ representing the maximum and minimum limits of E which are 90% and 80%, respectively. The difference of the current and the maximum and minimum limited energies are denoted, respectively, as K_1 and K_2 and expressed as:

$$K_1 = E - E_{\max} \tag{2}$$

$$K_2 = E - E_{\min} \tag{3}$$

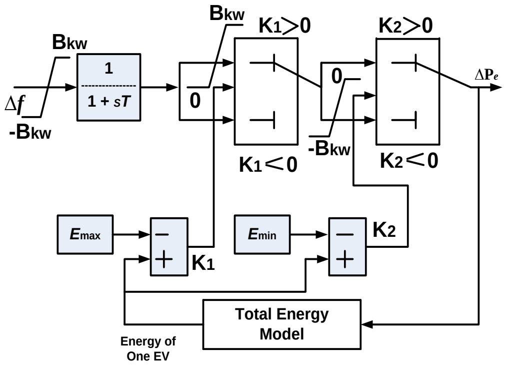

Figure 3. Lumped Plug-in EV Model

The energy storage model of plug-in EV, presented in Figure 4, is utilized to compute the energy storage in batteries of the local control center which acts as a communication medium between power grid and electric vehicles and regulates further the number of EVs.

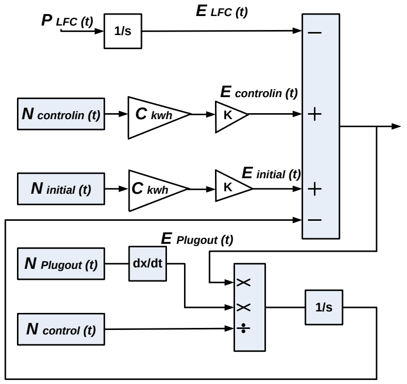

Figure 4. Stored Energy Model of a Typical Local Control Center

At any instant of the time interval (t), the number of controllable EVs in participation i.e. $N_{controllable}\,(t)$ is calculated as in Eqn. (4)

$$N_{controllable}\,(t) = N_{intial}(t) - N_{plugout}(t) + N_{controlin}(t) \tag{4}$$

$N_{intial}(t)$ – Initial number of controllable EVs at the start of the interval

$N_{plugout}(t)$ – Number of EVs changing state from controllable to driving during that time

$N_{controlin}(t)$ – Number of EVs changing state from charging to controllable at that time period

Energy expression is described by Eqn. (5) as:

$$E_{control}\,(t) = E_{intial}(t) + E_{controlin}(t) - E_{plugout}\,(t) - E_{LFC}(t) \tag{5}$$

$E_{intial}(t)$ - Initial energy

$E_{controlin}(t)$ - Increase in the energy due to EVs

$E_{plugout}\,(t)$ - Reduction in the energy due to plug out

As energy is increased, the plug-in EV state also gets changed from charging to controllable by multiplying $N_{controlin}$ (t) and average charging energy (C_{kwh}). $E_{controlin}(t)$ is calculated by Eqn. (6) as:-

$$\begin{aligned} E_{controlin}(t) &= C_{\text{kwh}} * N_{controlin}(t) \\ &= C_{\text{kwh}} * N_{controlin}(t) \qquad \text{[kwh]} \end{aligned} \tag{6}$$

E_{LFC} – energy equivalent to LFC signal, calculated by integral of P_{LFC}, is expressed by Eqn. (7) as:-

$$E_{LFC}(t) = \int_0^t P_{LFC}\,(t).\,dt \tag{7}$$

P_{LFC} - Local center power

With the integration of EV, the complexity of the system as whole and hence the control burden increases but it also brings in the advantage of frequency stabilization in the event of contingencies.

4. CONTROL STRUCTURE AND OPTIMIZATION ALGORITHM

In this work, FOPID control structure optimally tuned using MVO has been implemented as the prime control scheme. The control structure and the MVO algorithm are explained as under:

A. FOPID Controller

Podlubny put forth the FOPID controller in the technical literature as reported in [43]. This proposition of a new control structure by Podlubny has invited the attention of the control community owing to its improved performance over conventional PID controller. The involvement of five parameters (K_P, K_I, K_D, λ, and μ) not only significantly enhances its design flexibility but also makes it capable to perform special control functions. As per [44], FOPID proves to be better than PID controller in both fractional and integer order systems. Many different design approaches are reported in [45], [46]-[48] for FOPID. The transfer function of FOPID controller is described as in Eqn. (8).

$$G_C(s) = K_P + \frac{K_I}{S^{\lambda}} + K_D S^{\mu} \quad (8)$$

Where, K_p is the proportional gain, K_I is the integral gain, K_D is the derivative gain, $\boldsymbol{\lambda}$ is the order of the integrator, and μ is the order of the differentiator.

B. MVO Algorithm

MVO, a recently proposed evolutionary algorithm [25], for optimization, is utilized in this study for optimizing the controller parameters. The algorithm derives its inspiration from the three phenomena i.e. the white hole, the black hole, and the wormhole as noticed in cosmology which are modeled suitably to execute the functions of exploration, exploitation and local search, respectively as is described in detail in [25]. Roulette wheel mechanism is used for the mathematical formulation of black and white hole tunnels besides executing the exchange process of the universe objects. The iterative process involves the sorting of the universes at each iteration based on the inflation rates, with one of them being chosen by the roulette wheel to have a white hole. The flowchart explaining the steps involved in implementation of the MVO algorithm is given in Figure 5.

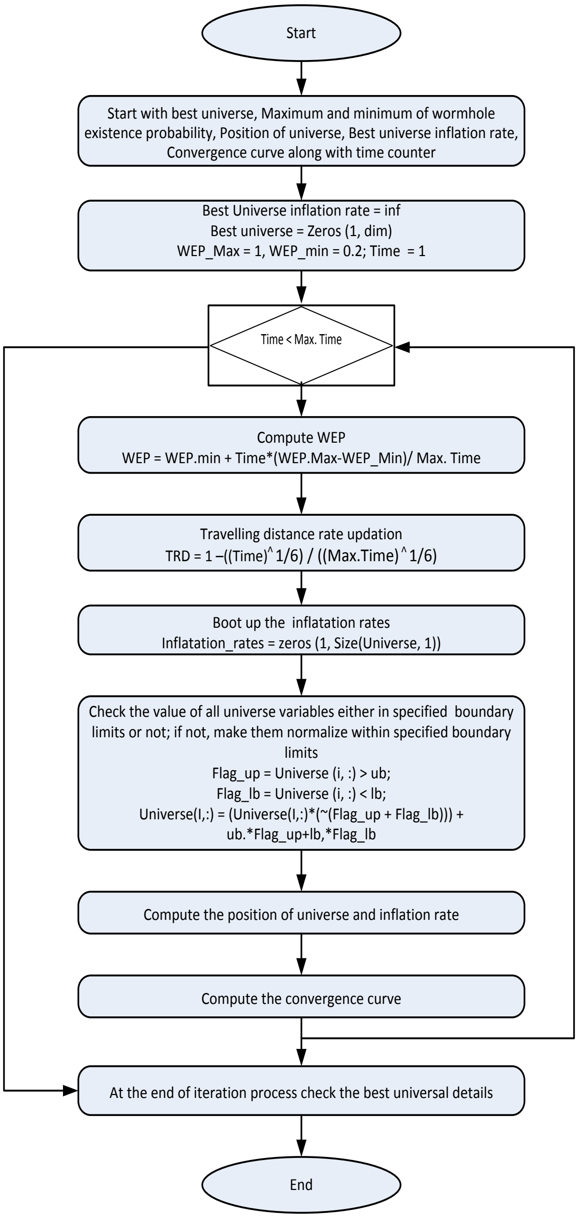

Figure 5. MVO Flow Chart

5. RESULTS AND DISCUSSION

The system model, as in Figure 2, is simulated using MATLAB and investigated under the following scenarios:

A. Performance evaluation of MVO algorithm vis-à-vis other algorithms
B. Design and implementation of FOPID controller and comparative analysis of performance
C. Impact study of Electric Vehicle
D. Sensitivity assessment with regard to parametric variations
E. Study under random step load change

Optimization algorithms were implemented through

MATLAB programs (.m files) and in the process Integral of Time Multiplied Absolute Error (ITAE), described in Eqn. (9), is used as the cost function which is one of the widely used cost functions that considerably improves the transient and steady-state response of the system [49].

$$ITAE = \int_0^T |\Delta f|.t.dt \quad (9)$$

Where, T is the simulation time and Δf is the change in frequency presented as:

In case of FOPID Control, values of gain parameters (K_P, K_I, K_D, $\boldsymbol{\lambda}$, μ) are considered to be constrained in the range of [0-2] and these gain parameters are optimized using MVO and, for comparison, using other optimization algorithms as well. The 10% step load change is applied in the auxiliary load (P_{L2}), connected in the system.

A. *Performance evaluation of MVO algorithm vis-à-vis other algorithms*

To establish the supremacy of MVO algorithm over other algorithms, the system of Figure 3 is investigated for frequency deviations with 10% step load change in the auxiliary load (P_{L2}) at t = 0 sec utilizing FOPID controller, optimally tuned using MVO and other evolutionary algorithms, namely DE, PSO, TLBO, and ALO, respectively. The qualitative relative performance of these implemented algorithms, in respect of system frequency deviations, is shown in Figure 6, zoomed in for low values of x axis so as to better understand the performance of various algorithms under transient conditions with clarity, since asymptotically all algorithms perform almost equally. Each of the algorithms is iterated for 30 times. The quantitative comparison of the performance of these algorithms, in respect of minimum value of the ITAE, peak undershoots, and settling time, is presented in Table 3.

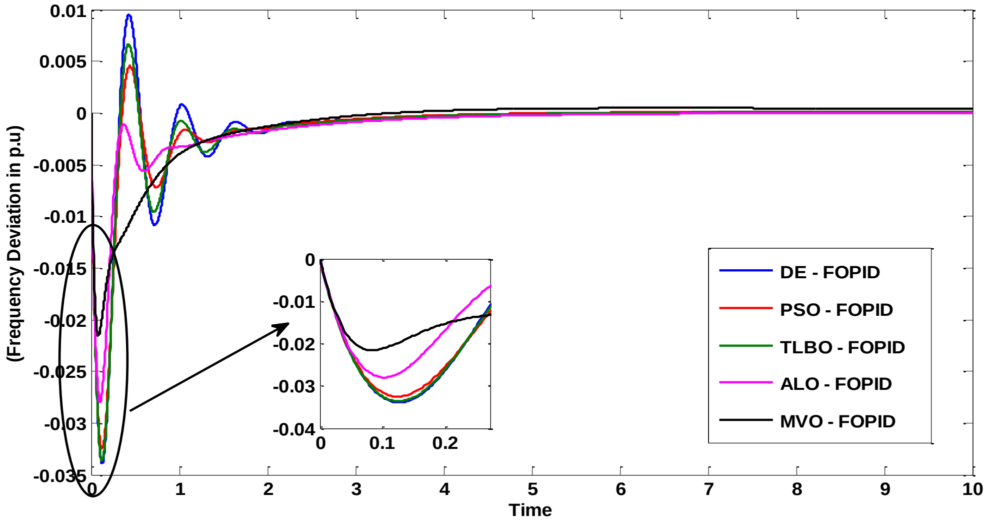

Figure 6. Frequency Deviation Responses

TABLE 3 COMPARISONS OF DIFFERENT OPTIMIZATION ALGORITHMS

Controllers	DE-FOPID	PSO-FOPID	TLBO-FOPID	ALO-FOPID	MVO-FOPID
ITAE	0.0307	0.0295	0.0291	0.0277	0.0260
Settling Time	3.0891	3.0471	3.1806	3.6392	2.6605
Peak Undershoot	0.0339	0.0325	0.0336	0.0280	0.0216
Controller Parameters					
λ	0.1555	0.1749	0.1349	0.0011	0.675
μ	0.0022	1.5089	0.7171	1.2631	1.5081
K_P	1.6863	1.9121	1.7847	1.8285	1.9358
K_I	1.2937	1.5136	1.4789	1.8518	0.9226
K_D	0.8143	0.0278	0.1040	0.2363	0.3226

As can be seen from Figure 6 and Table 3, with MVO the response is less oscillatory besides giving the least peak undershoot. Not only this, the settling time and the values of the performance index i.e. ITAE are also the minimum with MVO as compared to other algorithms. It can therefore, be concluded that the MVO algorithm has a definite edge over all other algorithms.

B. Design and implementation of FOPID controller and comparative analysis of performance

Having established the supremacy of the MVO algorithm in section *A*, comparative study of FOPID controller against FOPI and PID controllers with and without EV is presented in this section with all controllers optimally tuned using MVO algorithm. The system model as shown in Figure 2 is investigated under the step load change of 10% in auxiliary load (PL_2). Figure 7, zoomed in for low values of x axis so as to give a clear depiction of the performance of various algorithms under transient conditions, since eventually for sufficiently large values of time all algorithms perform almost equally. Figure 7 depicts the comparative performance of the controllers in terms of frequency deviations, whereas, quantitative comparison of the performance is presented in Table 4 w.r.t minimum values of ITAE, settling time, and peak undershoots as the performance indices.

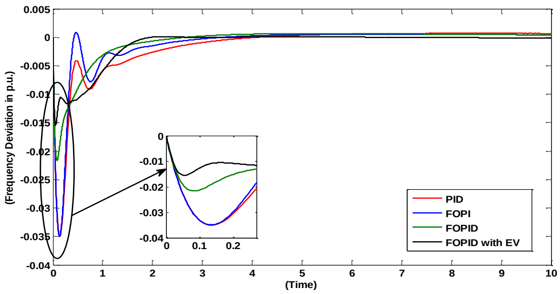

Figure 7. Frequency Deviation Responses

TABLE 4. COMPARATIVE ANALYSIS OF DIFFERENT CONTROLLERS

Controllers	MVO- PID	MVO- FOPI	MVO- FOPID	MVO- FOPID with EV
ITAE	0.0408	0.0308	0.0260	0.0103
Settling Time	4.0219	2.9974	2.6605	1.7476
Peak Undershoot	0.0350	0.0345	0.0216	0.0155
Controller Parameters				
λ	--	0.675	0.675	0.695
μ	--	0.008	1.5081	1.5110
K_P	1.0233	1.5946	1.9358	1.8547
K_I	0.1423	0.5226	0.9226	0.8134
K_D	0.0199	--	0.3226	0.5105

From Figure 7 and Table 4, it is established very clearly that the MVO optimized FOPID controller outperforms all other controllers in effectively regulating the frequency of the AC microgrid against small step load disturbance. The response with FOPID controller is less oscillatory, the values of the cost function are the least, peak undershoots are small, settling time values are the least.

C. Impact study of Electric Vehicle

The effect of EV on the frequency regulation of AC microgrid is investigated. The EV, based on the transfer function model shown in Figure 3, is implemented in the linearized system model of Figure 2 with FOPID, with its parameters optimized using MVO, as the controller used. The performance of the system under the step load change of 10% in auxiliary load (P_{L2}), with and without EV, is depicted in Figure 7 and Table 4 wherefrom it becomes amply clear that the EV has a very positive impact on the system frequency regulation and stabilizes the frequency with transients suppressed faster.

D. Sensitivity assessment with regard to parametric variations

The system performance is evaluated against the parametric variations so as to assess the robustness of the FOPID controller and the MVO algorithm as used for tuning of controller parameters. Figure 8 presents the frequency deviation responses with the variation in all parameters, as given in Table 2, by ± 25 but keeping values of FOPID controller parameters constant. It is evident from Figure 8 that the proposed control approach is robust in the face of parametric variations and thus proves to be robust and less sensitive to the variations. The controller parameters also are not required to be retuned for parametric variations and the response is still maintained stable and effective.

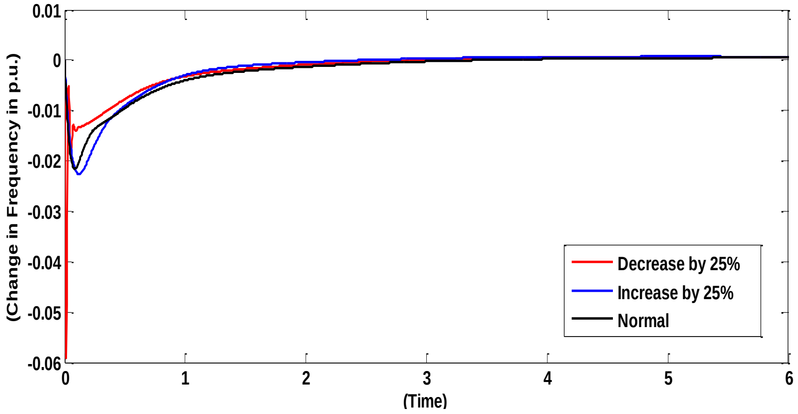

Figure 8 Frequency Deviation Responses

E. Study under random step load change

To analyze the robustness of the proposed MVO optimized FOPID control under random step loading conditions, the pattern as shown in Figure 9, variable both in duration and magnitude, is considered as the disturbance which the system of Figure 2, with and without EV, is subjected to. For comparative analysis, MVO tuned PID controller is also implemented for this case study. As can be seen in Figure 10, the transient response of the system makes it clear that FOPID controller is robust against random load changes and again in this case also proves to be better than the PID controller.

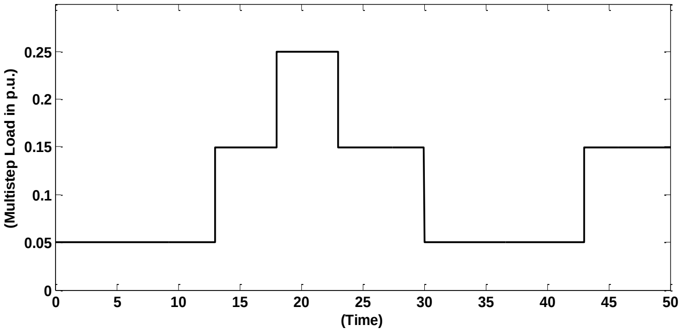

Figure 9 Random Loading Pattern

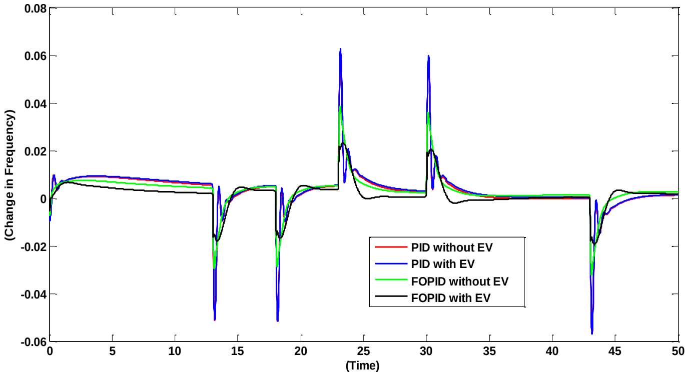

Figure 10 Comparison of Frequency Deviation

6. CONCLUSION

FOPID controller optimized with MVO algorithm is proposed and implemented as the control scheme for frequency regulation in an AC microgrid. Comparative performance analysis of the MVO algorithm vis-à-vis the other evolutionary algorithms is established and then the effectiveness of MVO is demonstrated in optimizing the controller parameters. The novelty of the work is in the application of the MVO algorithm for optimal tuning of the controller parameters. Further, the positive effect of EV on frequency regulation is also demonstrated. The proposed control scheme is tested for robustness against system parametric variations besides the random step load changes and proved to be effective. The findings are indicative of the potential use of MVO algorithm for optimal tuning of parameters of the controller as used for frequency regulation in AC microgrid systems.

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